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# ***KEPLER*** Mission Status

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**Abstract.** Kepler is a Discovery-class mission designed to determine the frequency of Earth-size and smaller planets in and near the habitable zone (HZ) of dwarf stars. The instrument consists of a 0.95-m aperture photometer capable of doing high precision photometry of more than 100,000 late-type main sequence stars to search for patterns of transits. Multi-band ground-based observation of over 2 million stars is currently underway to estimate the stellar parameters and to choose appropriate targets. The association of planet size and occurrence frequency with stellar mass and metallicity will be investigated. At the end of the four year mission, several hundred terrestrial planets (i.e., planets up to twice the diameter of the Earth) should be discovered with periods between one day and 400 days if such planets are common. As many as 100 Earth-size planets in the HZ could be discovered. A null result would imply that terrestrial planets are rare. The scientific community is invited to participate through the Participating Scientist, Guest Observer and Data Analysis programs.

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## 1. Introduction

Since the first discoveries of extrasolar planets around normal stars in 1995, approximately 200 such planets have been discovered. At least 6% of solar-like stars show the presence of giant planets with orbital periods of a few years or less (Marcy et al. 2006). Most of these are very massive, often exceeding that of Jupiter and Saturn, but recent observations have found planet masses as low as 7.5 times that of Earth (Rivera et al 2005). Furthermore most have semi-major axes less than 1 AU and have high orbital eccentricities. The surprisingly small values for the semi-major axes imply that they form at several AU but then lose momentum to the accretion disk and spiral inward. It is unclear what processes terminate the inward motion and what fraction of planets fall into the star. However it is obvious that the inward motion of the giant planets will remove smaller planets by scattering them either into the star or out of the planetary system. It is also possible that the stars not showing the presence of giant planets are devoid of all planets because the giant planets merged with the star after their inward migration. Hence planetary systems with terrestrial planets might be rare. It is also possible that most stars did not form giant planets, but only terrestrial ones. Wetherill (1991) has shown that in such cases, many terrestrial planets could form over a large range of semi-major axes.

The Kepler Mission is designed to discover hundreds of terrestrial planets in and near the habitable zone (HZ) around a wide variety of stars. For orbital periods less than a week, hundreds of transits will be observed during the four year mission so that planets as small as Mars can be detected. Kepler is a PI-lead mission and was competitively selected in December 2001 as NASA Discovery Mission #10. It is scheduled to launch in November 2008 into an Earth-trailing orbit. A description of the mission, its status, and the expected science results are presented.

## 2. Scientific Goals

The general scientific goal of the Kepler Mission is to explore the structure and diversity of planetary systems with special emphasis on determining the frequency of Earth-size planets in the HZ of solar-like stars. This is achieved by surveying a large sample of stars to:

- Determine the frequency of Earth-size ($R_\oplus$) and larger planets in or near the habitable zone of a wide variety of spectral types of stars
- Determine the distributions of sizes and orbital semi-major axes of these planets
- Estimate the frequency of planets orbiting in multiple-star systems
- Determine the distributions of semi-major axis, albedo, size, mass, and density of short period giant planets
- Identify additional members of each photometrically-discovered planetary system using complementary techniques
- Determine the properties of those stars that harbor planetary systems.

## 3. Photometer and Spacecraft Description

The instrument is a differential photometer with a 100 square degree field-of-view (FOV) that continuously and simultaneously monitors the brightness of at least 100,000 main-sequence stars. The brightness range of target stars is from visual magnitude 9 through 15. The photometer is based on a modified Schmidt telescope design that includes field flattener lenses near the focal plane. Figure 1 is an isometric view of the photometer. The corrector has a aperture of 0.95-m with a 1.4-m diameter F/1 primary. This aperture is sufficient to reduce the Poisson noise to the level required to obtain a $4\sigma$ detection for a single transit from an Earth-size planet transiting a 12th magnitude G2 dwarf with a 6.5 hour transit. The focal plane is composed of 42 1024x2200 backside-illuminated anti-reflection coated CCDs with 27 micron pixels. Each pixel is 3.98 on the sky. The point spread function is 1 to 1.5 pixels depending on the location on the focal plane and on the exact distance of the CCD surface from the focal surface.

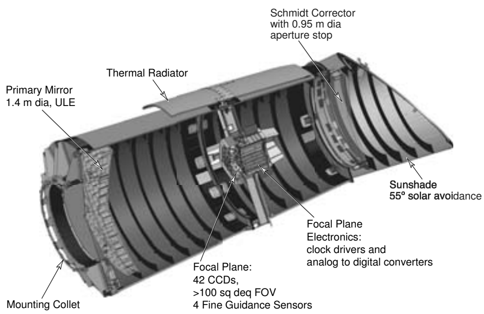


Figure 1. Isometric view of the Kepler photometer.

The detectors are at prime focus. Two X-band omni-antennae are used for uplink commanding and for engineering data downlink on a twice weekly basis. Approximately 2 Gbits/day of science data are recorded and then transferred to the ground every 31 days when contact is made with the Deep Space Network. Every 91 days, the spacecraft is rotated 90 degrees around the optical axis to keep the sunshield toward the Sun and the radiator in shadow (see Fig. 2).

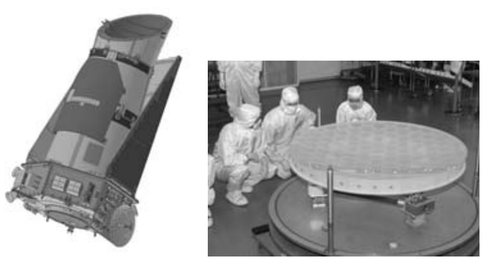

Figure 2. **Left:** Integrated spacecraft and photometer. **Right:** Light-weighted primary mirror being inspected at BATC before being sent out for coating.

The spacecraft will be placed in an Earth-trailing heliocentric orbit. The heliocentric orbit provides a benign thermal environment to maintain the stability of the telescope metering structure and thus the photometric precision. This orbit also allows continuous viewing of a single FOV for the entire mission without the Sun, Earth or Moon obtruding. The orbit has a 53 week period that slowly increases the range to the spacecraft so that it is about 0.4 AU from Earth after 4 years. As the range increases, the telemetry volume must decrease and therefore the number of stars monitored will be reduced from about 170,000 targets to 100,000 by the end of the mission. Stars found to be particularly noisy or having low potential to show the presence of transits (i.e., large, but dim stars) will be removed from the target list and no longer monitored.

Both the photometer and the spacecraft are being built by the Ball Aerospace and Technology Corporation (BATC) in Boulder, Colorado. JPL manages mission development. NASA Ames manages mission operations, data reduction, and scientific analysis. LASP in Boulder, CO conducts mission operations. All data are archived at the Space Telescope Science Institute (STScI) and will be made available to the science community from the MAST

All the detectors have been received, tested, qualified, and are now being mounted to modules that will plug into the focal surface. Figures 2 show the optics before being sent out for coatings. Assembly and testing of the components is underway. Assembly and testing of the photometer will start in mid 2007.

## 4. Scientific Approach

To achieve the required photometric precision to find Earth-size planets, the photometer and the data analysis system must be designed to clearly detect the very small changes  100 ppm) in stellar flux on the time scale of hours that are characteristic of transits by terrestrial planets. The Kepler Mission approach is best described as differential relative photometry :

- Target stars are always measured relative to the ensemble of similar stars on the same part of the same CCD and read out by the same amplifier during each 91 day period
- Only the time change of the ratio of the target star to the ensemble is of interest
- Only decreases from a trend line based on a few times the transit duration are relevant (long-term stability of the trend is not required)
- Target star and ensemble stars are read out every five seconds to avoid the effects of gain drift and saturation
- Correction for systematic errors is critical; motion of the image across the CCD is a major concern.

Photometry is not done on the spacecraft. Instead, all of the pixels associated with each star image and the collateral, bias, and smear pixels are sent to the ground for analysis. This choice allows us to compare different photometric analysis methods and to use different approaches to reduce common-mode and systematic errors. Current plans include two processing pipelines to do both aperture and difference image analysis and then comparing the results.

A pattern of at least three transits that shows that the orbital period repeats to a precision of at least 10 ppm and that shows at least a $7\sigma$ detection is required for any discovery. A detection threshold of $7\sigma$ is required to avoid false positives due to random noise. The mission is designed to provide a lifetime of four years to allow four transits in the HZ of a solar-like star to be observed resulting in a higher recognition rate. Note that transit signatures with a mean detection statistics of $8\sigma$ will be recognized 84% of the time whereas those with a mean of $7\sigma$ will be recognized only 50% of the time.

Classical signal detection algorithms that whiten the stellar noise, fold the data to superimpose multiple transits, and apply matched filters are employed to search for the transit patterns down to the statistical noise limit (Jenkins et al, 2002). From measurements of the period, change in brightness and known stellar type, the planetary size, the semi-major axis and the characteristic temperature of the planet can be determined. The latter gives some indication of whether liquid water could be present on the surface, i.e. whether the planet is in the habitable zone.

## 5. Selection of target stars and field of view

Continuously monitoring approximately 100,000 quiet, late-type target stars will provide a statistically meaningful estimate of the frequency of terrestrial planets in the HZ of solar-like stars. A FOV centered on a galactic longitude of 76.5 deg and latitude of 13.3 deg satisfies both the constraint of a 55 degree sun-avoidance angle and provides a very rich star field (see Fig. 3). This location balances the falling area density of target stars with latitude against the very rapid decrease in the number of evolved stars that cause crowding. This FOV falls within the Cygnus-Lyra constellations and results in looking in a tangential direction from the galactic center.

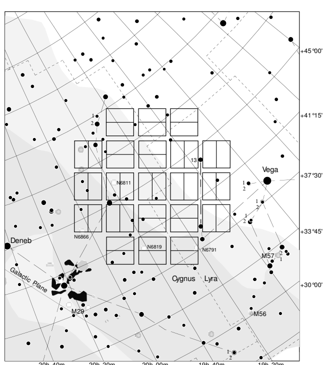


Figure 3. FOV for the Kepler Mission.

A ground-based observation program led by David Latham and Tim Brown is underway to observe $2x10^6$ stars in the FOV. A unique color-filter system based on both the JHK filters used for the 2MASS survey and the Sloan system filters g, r, i, & z augmented with a special filter sensitive to the magnesium lines is being used to identify both the luminosity class and spectral type of each star. These measurements are combined with the data on the 20 million stars in the USNO-B catalog to form the Kepler Input Catalog. From the combined observations, $T_{eff}$, log(g), [Fe/H], reddening, mass, and radius are estimated.

The resulting catalog allows the Kepler Mission to choose only F through M dwarfs and to exclude giants and early spectral types from the target list. By classifying stars down to $K$=14.5 magnitude for which we have complete photometry and the three 2 MASS bands available, several thousand M dwarfs can be found and put on the target list. Because of their small diameter, these stars will provide sufficient signal-to-noise (SNR) for detection of terrestrial-size planets even though they are dimmer than the majority of other targets. The Kepler results for the frequency of terrestrial planets orbiting M-dwarfs are important because most nearby stars are M-dwarfs.

After launch, asteroseismology will provide additional information on a substantial fraction of the target stars (Christensen-Dalsgaard et al. 2007). In particular, frequency spacings will yield accurate radii and in many cases measures of stellar ages.

## 6. Expected results

Estimates of the frequency and distribution of terrestrial planets are very uncertain because there are no observations of terrestrial planets (Lissauer 1995). Although observations of giant planets indicate an increasing frequency with decreasing mass and some authors theorize that more than one terrestrial planet will be found in a typical HZ (Gillon et al, 2005), only a search capable of finding many terrestrial planets over a large range of semi-major axes can provide a meaningful estimate of their frequency and provide a meaningful null result if none are found. Nevertheless, some assumptions about the frequency and distributions of extrasolar planets must be made to assess the capability of the Kepler Mission. The following discussion is presented in that light; the results shown are not a prediction, only an assessment of capability given the assumptions. The reader can scale the results to fit their intuition.

Initially large planets in short period orbits with three or more transits will be detected and confirmed with follow-up observations. As the mission duration lengthens from months to years, the envelope of discovery capabilities will expand to the detection of smaller planets and longer orbital periods. Larger planets will have a high SNR and will be detected before the smaller planets. The latter can be detected only when a sufficient number of transits have been observed to increase the total SNR above 7. After a year even planets as small as Mars in 4 day orbits should be detectable.

To estimate the number of planet discoveries expected as a function of planet size, orbital semi-major axis, and stellar type, a model of a planetary system was convolved with both the distributions of stars in the FOV and the system response. The abundances, spectral, luminosity, and brightness distributions of stars in the Kepler FOV are taken from the Besancon model (Robin et al. 2003) integrated over the Kepler FOV and accounting for the spectral response of the detectors and assuming the stellar noise is red, that is, similar to the Sun. To assess the level of resources needed to examine the expected number of candidates, the planetary model makes the assumption that each star has a planetary system with eight Earth-size planets positioned outside the HZ of the star and that there is one terrestrial-size planet in its HZ. It is assumed that planets have semi-major axes similar to those already found for extrasolar giant planets, i.e., at 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, & 1.5 AU. Because of considerations of orbital stability, such a close spacing of planets is unphysical. The results are shown only to indicate the number of planets that could be detected at representative values.

The model treats planets in the HZ differently than those placed outside the HZ. Here the objective is to determine the smallest possible planet that provides a SNR greater than the $7\sigma$ threshold value. For this calculation, the diameter of the terrestrial-size planet placed in the HZ of each star is systematically varied between that of Mars to twice the radius of Earth (0.53, 1.0, 1.3, 2.0 $R_\oplus$) and the smallest detectable planet size is tabulated. The capability to detect small planets is critical because such a non-detection rules out a large range of planet sizes and because their detection provides information on the small end of the distribution of planet sizes. Figure 4 shows how many planets of each size can be detected for a four-year mission and for stellar types from F7 to M7. The model shows that terrestrial planets in the HZ can be found only for G dwarfs and later. This result is dictated by the requirement to have at least three transits for a valid discovery and because planets in the HZ of early spectral types have orbital periods exceeding 1.5 years. However, if the mission duration is extended to six years, the HZ of F stars can be searched and an additional 100 terrestrial-size planets could be discovered in HZ of F and later type dwarfs because of the increased number of transits.

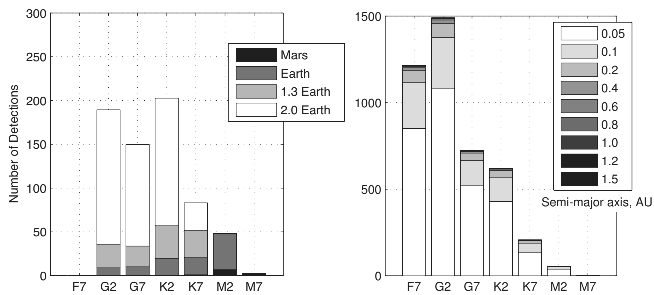


Figure 4. **Left:** The number of terrestrial-size planets that could be discovered in the HZ as a function of stellar spectral type, semi-major axis, and planet size. It is assumed here that each target star has one planet of the size specified in its HZ. **Right:** The number of planets that could be discovered if each star has an Earth-size planet at each of eight of the locations indicated. This figure does not include planets that might be in the HZ of each spectral type. For the assumption of only 1 Earth-size planet per star outside the HZ, the results should be reduced by a factor of 8.

It is clear from Figure 4 (left) that approximately 4,200 Earth-size planets could be found outside the HZ of the target stars if each position were occupied by an Earth-size planets. Although these values are expected to be much too high, they show the dependence of the expected results on the semi-major axes of the planets. Assuming that there is only one Earth-size planet interior to the HZ reduces the results shown in Figure 4 (right) by a factor of 8 and provides a probably more realistic estimate of 500 planets. However, if planets larger than Earth-size are common, they will produce higher SNR than assumed here, will be more easily detected around the many dim stars monitored in the Kepler survey, and will thereby increase the number of discoveries. It is also worth noting that over the duration of a four year mission, the number of transits in a pattern will exceed 400 for the shortest period orbits and thus make possible the detection of planets as small as Mars and Mercury.

Figure 5 shows predictions of the dependence on planetary radius on mass for different compositions ranging from mostly water to mostly iron (Fortney et al. 2006). The Kepler Mission is expected to get planet diameters accurate to a few percent from measurements of transit depth and a determination of the stellar size from parallax, effective temperature, and the bolometric magnitude. For the brighter stars, asteroseismic analysis of the data will also be used to obtain the stellar size. During the mission lifetime, the HARPS-North instrument will measure differential radial velocities to 60 cm/s (Mayor et al. 2003) for identifying stars with planets of known period and phase. Thus the combined observations should be sufficient to determine the density and thereby identify the composition of those terrestrial-mass planets in short period orbits around bright stars.

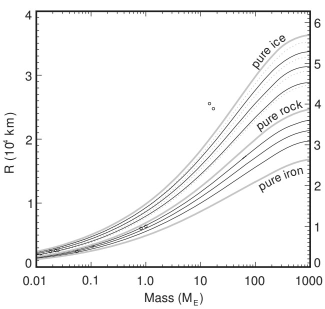


Figure 5. Predicted size vs mass for planets of different compositions. (Fortney et al. 2006)

With the ability to discover up to 100 Earth-size planets in the HZ and several hundred more interior to the HZ, the number of Earth-size and larger planets orbiting could exceed that of extrasolar giant planets. If planets twice the size of the Earth are common, then the number of discoveries could exceed 1000. If only 10% of the stars have such planets, useful correlations between the frequency of planets and with stellar type and metallicity could be made. If no terrestrial-size planets are found within the entire range of semi-major axes searched, then they must be rare and theories on terrestrial planet accretion and migration will need to be re-examined.

## 7. Validation of Planet Detections

Before a candidate detection can be considered to be a valid planet, a rigorous validation process must be executed to ensure that it is not due to some other phenomenon. Two types of false positives are expected; those due to statistical fluctuations in the data and those due to astrophysical objects that produce light variations that mimic planetary transits. The elaborate protocol that is planned to eliminate these false positives is treated at length in Borucki et al. 2004, Gautier et al., this volume.

## 8. Control Group

To generate valid correlations between the characteristics of the discoveries with those of the stars with planets, it is necessary to determine the characteristics of a control group of stars. For example, to associate the frequency of terrestrial planets with the metallicity of the stars they orbit, the metallicity of a representative sample of target stars must be known. For independent variables that have a low occurrence frequency in a particular range, the number of members in the control group must be chosen large enough to provide an accurate frequency determination. The error rate of the classification of the stars must also be considered. For example, for some spectral types, it is difficult to separate giants from dwarfs. Although most the target stars will be dim, the brightest members of each spectral type will be most productive in providing discoveries. Further, brighter stars of a particular spectral type, luminosity class, and metallicity will be nearer than the dimmer stars. Therefore, because of the expected variation of stellar properties with distance, the control group must allow the dependence on distance to be estimated.

Probably the most difficult independent variable that must be determined is the stellar multiplicity. One of the objectives of the Kepler Mission is to measure the correlation of planetary characteristics with the stellar multiplicity. Bright binary stars with similar mass ratios and short period orbits will be readily recognized by their spectra or radial velocity variations. Binary stars with high mass ratios and short orbital periods become single lined binaries that can only be recognized by velocity variations or an excess flux using parallax, Teff and bolometric magnitude (Koch et al, 2006). Although short period binaries can be quickly recognized, recognition of the many binaries that have periods of years to centuries can only be done by high precision radial velocity observations over a very long period (i.e., of order the orbital period). As most of the target stars will be 12th magnitude and dimmer, the determination of multiplicity will require long integration times at large aperture telescopes over a period of years.

The current plan is to select 100 F, 400 G, 400 K, and 100 M dwarfs for a control group of 1000 members. Larger numbers of G and K stars will be chosen because they are predicted to be the most productive targets. Although a fraction of each group that will be selected from the most distant stars, most will be selected from the brighter candidates to sample the most productive stellar population and to obtain accurate determinations of the stellar parameters such as size, metallicity, multiplicity, and age. Division of each group into 10 bins should provide statistically meaningful answers to many hypotheses. For example, are the statistical dependencies of the single-star G dwarfs different from those of the multiple-star G dwarfs with respect to metallicity?

## 9. Opportunities to Participate

It is expected that three opportunities to participate in the Kepler Mission will be available; Participating Scientist (PS), Guest Observer (GO), and Data Analysis (DA) Programs. The first opportunity to participate will be advertised in 2007 for the PS Program.

The PS Program will encourage investigations that are relevant to extra-solar planets and complement the research planned by the Mission Team. Investigations can be analytical, observational, or theoretical in nature. Examples of appropriate analytic programs include: modeling eclipsing binary systems to determine the characteristics of the stars and planets, and measuring and modeling timing variations in the epoch of transits to detect non-transiting planets. Examples of ground-based observational programs include those designed to fully characterize those stars found to have planets, high-precision radial velocity measurements to determine the mass of the planets detected from transits or from reflected light, confirmation of transits or efforts to detect atmospheric absorption, and observations that verify that the transit signal is coming from the target star rather than a background star.

The GO Program will accommodate those investigators who wish to make astrophysical measurements of the many different types of objects in the Kepler FOV. Generally, these targets will be different than those chosen for the transit search. Examples include variable stars of all types, distribution and time variation of zodiacal light, and extragalactic objects. It is expected that a total of about 3000 additional targets at any one time will be available and that these selections can be changed at intervals of 3 months. Most of the targets will be observed at a cadence of once per 30 minutes, but a subset of 25 stars can be observed with a one minute cadence. All targets must be within the active area of the Kepler FOV because the FOV will not be moved during the mission. For stars already on the Kepler target list, the GO investigators will be referred to the DA Program. The Kepler target list will be available prior to the release of the announcement of opportunity (AO) to allow investigators to plan appropriate requests. Release of the AO is expected after successful on-orbit operation is attained.

Investigators desiring to analyze data from targets already on the Kepler target list will apply to the Data Analysis Program (DAP). DAP is an opportunity for the scientific community to perform data mining on the Kepler database. Examples of potential uses for the data are validation of planetary detections, exoplanet searches using alternative techniques, analysis of stellar activity cycles, white-light flaring, frequency of Maunder minimums, distribution of stellar rotation rates, etc.

A data release policy has been developed to release mission data at the earliest time that allows for data calibration and validation and insures against false-positive planetary detections. The first three-month data set will be released approximately one year after commissioning and then supplements will be released annually. Publicly released Kepler observations will be freely available to all interested parties for data mining. The data will be archived In the Multimission Archive at Space Telescope (MAST) and supported for at least five years after the end of the mission.

## 10. Summary

The combination of both space-based and ground-based observations gives the Kepler Mission the ability to determine the frequency of occurrence of Earth-size planets, their size, orbital period, semi-major axis, and their association with stellar properties for a very large sample of stars. For a smaller number of bright stars, it will also characterize terrestrial planets with respect to size, mass, density, and composition. In summary, Kepler should produce an excellent estimate of the size distribution of terrestrial planets. Several opportunities for members of the science community will be available.

## 11. Acknowledgements

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